Measurement Techniques for Cryogenic Low Noise GaAs and InP HEMT Amplifiers

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ABSTRACT

With operational spacecraft in excess of 10 astronomical units from earth, NASA's Deep Space Network requires sensitive receivers for detection of weak spacecraft signals. The following article describes the sequence of measurements that lead to the development of cryogenically cooled HEMT low noise amplifier packages that are installed in the antennas of NASA's Deep Space Network. Also discussed is equipment used and results of ongoing work.

1. INTRODUCTION

Development of low noise amplifiers (LNAs) is a process involving several steps. The process begins with on wafer measurements of *die form devices*. Current versus voltage (I-V), DC transconductance (Gm), and scattering (S) parameter measurements are made at room and cryogenic temperatures. This data is fit to device models using computer aided design (CAD) tools. The device models are used to design low noise amplifier circuits at 2.3 GHz (S-band), 8.45 GHz (X-band), and 32 GHz (Ka-band). The module is assembled in a class 100,000 clean room. The module typically consists of three stages of amplification for S and X-band and four stages for Ka-band. This ensures a minimum gain of 30dB. This is required to minimize the noise contribution from room temperature components which follow the LNA. The completed amplifier module is measured in a cryogenic test-bed to determine its noise temperature and gain versus frequency. This testing may be repeated several times if adjustment of various circuit components is necessary. These adjustments optimize the performance of the amplifier at the specified frequency of operation. After optimization, the module is integrated with the other components used with it as part of a working system. These components normally consist of isolators, filters and any adapters that may be required. This *string* of components is measured for input noise temperature and gain versus frequency at the operational cryogenic temperature of approximately 6 kelvin. This ensures there are no unwanted interactions between the components. The string is integrated into a closed cycle refrigerator (CCR) which includes the necessary room temperature to cryogenic microwave transition. The complete CCR is tested as a package. The CCR is integrated as a subsystem with the microwave feed subsystem components into an antenna system.

2. PROBE STATION MEASUREMENTS

The first step in the process of developing HEMT (High Electron Mobility Transistor) LNAs is probe station measurements[1] of both DC (I-V and Gm characteristics) and S-parameters. For the purpose of these measurements the Jet Propulsion Laboratory (JPL) purchased and modified a cryogenic probe station from Desert Cryogenics (see figure 1). The probe station has the capability of making these measurements at both room temperature (294kelvin) and cryogenic temperatures (below 25kelvin). This station consists of a Gifford-McMahon (GM) closed cycle refrigerator mounted in a vacuum housing. The GM refrigerator is used to cool a copper plate that is connected to the refrigerator with fine gauge copper welding cable. This reduces the mechanical vibration from the refrigerator drive motor. This mechanical vibration would make it nearly impossible to probe these devices. The microwave probes are connected to an end plate via a G10 fiberglass tube. This provides both thermal isolation and mechanical rigidity. The end plate is attached to a multi-axis positioner. It has 3 degrees of translation and one degree of rotation. The vacuum integrity of the probe positioning assembly is maintained through the use of metal bellows, which allows for movement of the probes. The necessary visibility for probe positioning is provided by using a quartz window in both the first stage heat shield lid and the vacuum housing. Both windows are located at the top of the vacuum housing. An optical microscope suspended above them permits viewing while the probe positions are manually adjusted with micrometers. DC bias is applied via the center and outer conductors of the microwave probes. The probes are connected to the instrumentation outside the vacuum vessel with copper plated stainless steel semi-rigid coaxial cable. The coaxial cable passes to the outside through a metal tube containing an o-ring, which is compressed against the outside of the cable.

An HP8510C Vector Network Analyzer (VNA) and an HP4155A Semiconductor Parameter Analyzer are connected to the probe station. The 4155A supplies DC bias to the devices through the internal bias tees of the network analyzer. The operational frequency range of this system is 1-50GHz. Data acquisition is controlled via a PC based computer with a National Instruments[2] PCI-GPIB interface card. A program developed by Mikeal Garcia[3] is used to automate the process of measuring S-parameters (see figure 2) and extracting the small signal transistor model. This program, called Milou, has a user-friendly interface and controls both the 8510C and the 4155A in automated modes. Milou greatly simplifies the process for device model extraction as Milou makes the necessary measurements, calculates component values, and provides error calculation. These values are used in the CAD software MMICAD[4] to develop working circuits for use in the amplifier module.

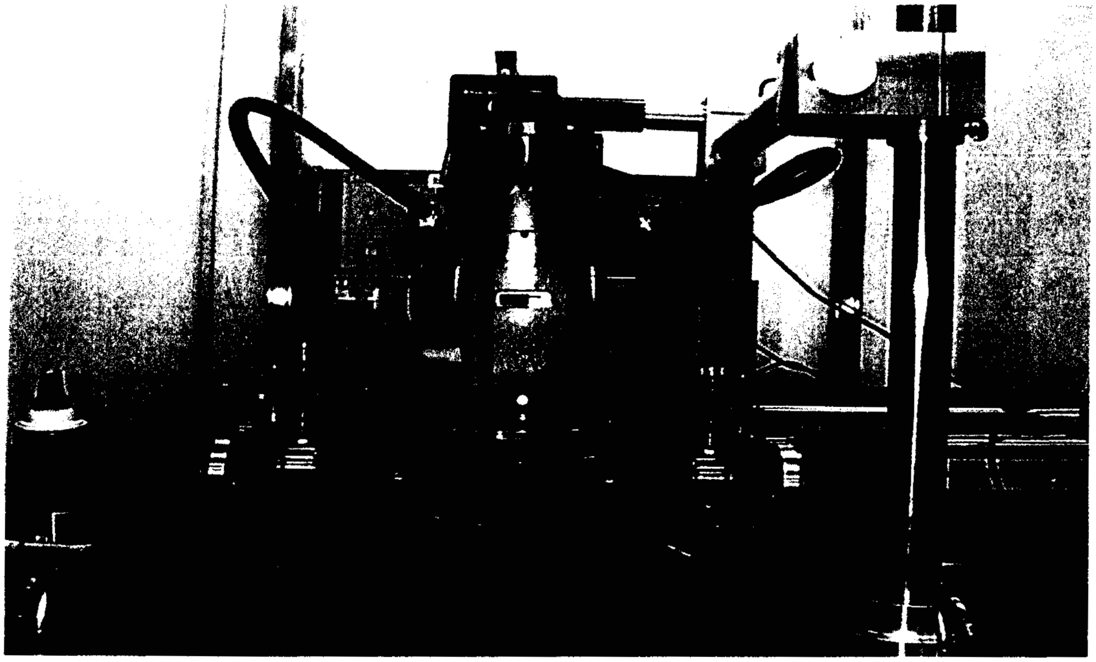

Figure 1. Cryogenic Probe Station capable of room temperature and cryogenic, DC and S-parameter measurements.

National Instruments LabVIEW programs developed at JPL are used to acquire I-V and Gm data (see figure 3).

3. AMPLIFIER MODULE MEASUREMENTS

A basic piece of equipment needed for cryogenic noise measurements of completed amplifier modules is a cryogenic test-bed capable of cooling the amplifier under test to its operational temperature (typically 15 kelvin or less). The test bed, shown Figure 4, consists of a vacuum housing, a 2 stage Gifford-McMahon helium refrigerator, and very low loss input and output R.F. transmission lines. These lines are copper plated thin wall stainless steel to provide low insertion loss and low thermal leakage from the outside room temperature to the internal 15 kelvin environment.

The amplifier module is placed in the test-bed and cooled to cryogenic temperature. A 20dB attenuator is connected to the amplifier input. The cryogenic attenuator method using an HP8970 Noise Figure Meter is used to measure input noise temperature and gain versus frequency[5]. In this technique a cold load is provided when the diode noise source is "off". In this state the source noise temperature applied to the DUT is equal to the physical temperature of the cryogenic pad (about 15K) plus a small contribution (about 3K) from the ambient temperature noise diode as attenuated by the cryogenic input transmission line and 20 dB cryogenic attenuator. Turning the 9000 Kelvin noise diode "on" provides the "hot" load. After attenuation by the cryogenic attenuator and low loss input transmission the noise power at the DUT input is about 90K. These "cold" and "hot" load temperatures of 18K and 90K are satisfactory for the measurement of amplifiers having less than 50K input noise temperature. This method was suggested by Bell Labs[6], then refined and used extensively by Dr. Sander Weinreb and Dr. Anthony Kerr at the National Radio Astronomy Observatories (NRAO). This method has several advantages over other methods. One advantage is that no mechanical switches are needed, hence rapid measurement speed is possible. A second advantage is that the "off" to "on" impedance changes of the diode noise source are reduced by the 20 dB cryogenic pad. Thirdly, the impedance and insertion loss of the transmission line connecting the cryogenic attenuator and the outside diode noise source contribute much smaller errors. At JPL, this cryogenic attenuator method has been combined with a high quality, commercial noise figure meter. The commercial noise figure meter provides the necessary wide frequency range tunable receiver and power meter that follow the DUT. Data acquisition is controlled via a PC based computer with a National Instruments PCI-GPIB interface card, National Instruments LabVIEW programs developed at JPL language are used. This noise temperature measurement system for cryogenic amplifiers covers the frequency range of 10MHz-50GHz. The amplifier module is also cooled without the attenuator and monitored on a spectrum analyzer for detection of any possible instability as varying input loads are applied. Module measurements of both GaAs and InP based amplifier modules are shown in Figure 5.

4. COMPONENT STRING MEASUREMENTS

After the amplifier module has been adjusted and measured it is integrated with the necessary filters, isolators, and adapters. This component string is placed in a larger test-bed and cooled with a waveguide attenuator at the input. A photo of a string in the test bed is shown in Figure 6. Data of several string measurements are shown in Figure 7.

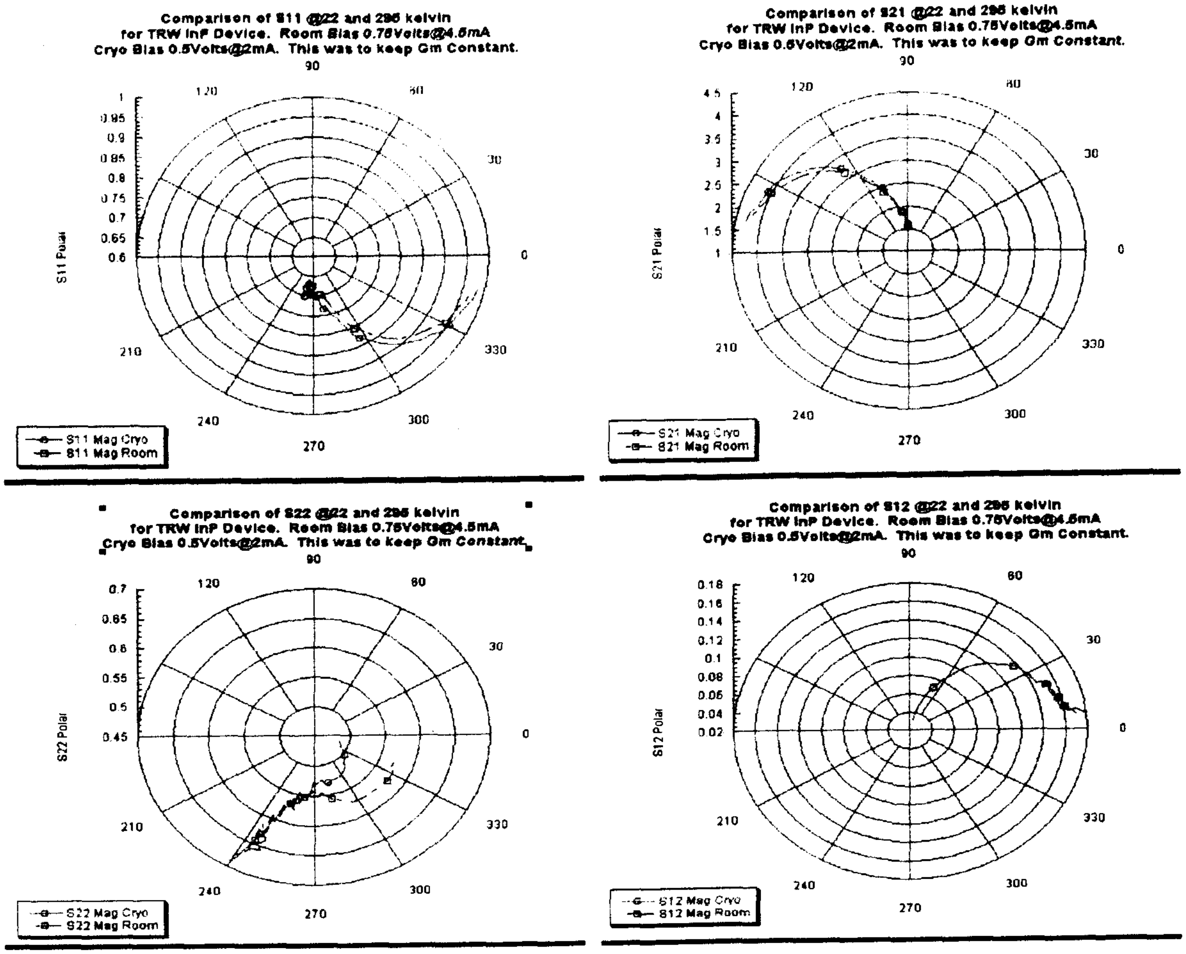

Figure 2. *S-parameters of an InP 300 micron device at a physical temperature of 295 and 22kelvin from 5 to 20 GHz.*

5. CCR MEASUREMENTS

Finally, the LNA is integrated into the CCR package (see figure 8). Current systems are using GM refrigerators built by Sumitomo[7]. They have 1.5 watts of cooling capacity at 4.2 kelvin. At this point in the process, typically the only unknown left is the microwave input thermal transition. Our standard method for measuring low noise amplifiers in cryogenic packages is the ambient load/cold sky method.

Dr. Charles Stelzried developed this method at JPL[8]. This method uses a calibrated test feedhorn[9], with a very low sidelobe pattern to minimize ambient noise pickup from the ground, placed at the room temperature input of the LNA. A radiometer is used to measure the power ratio between the sky and an ambient load placed over the feedhorn. This ratio, called the Y-factor, is used to calculate the LNA input noise temperature. This method is accurate for frequencies in the "microwave window" (about 1-12 GHz) where atmospheric weather effects are small, but must be done outdoors where the sky is unobstructed. Data from several CCR measurements are shown in Figure 9. These measurements are referenced to the room temperature waveguide input flange.

6. CONCLUSIONS

The data shown in figures 5, 7, and 9 indicates that while the GaAs devices seem to have stopped improving in performance versus physical temperature at 15 kelvin the InP device continues to improve below 15kelvin. Also 1/f noise does not seem to be a problem at the frequencies measured.

7. ACKNOWLEDGMENT

There are many centers around the world conducting research in the area of cryogenic low noise amplifiers. Though they are too numerous to mention here, we wish to acknowledge benefits we have received from our collaborations and discussions with them in the past and present. The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

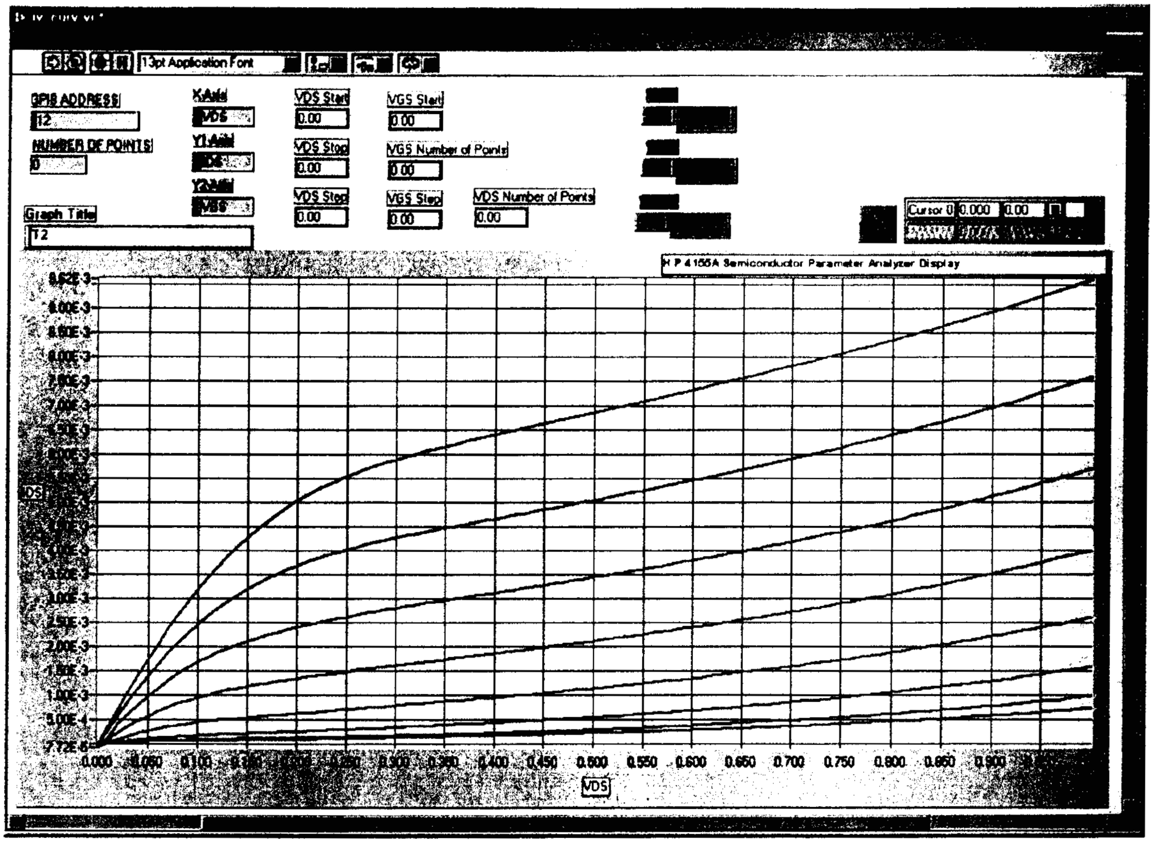

Figure 3. *IV Curves of 300 um InP device at 22kelvin*

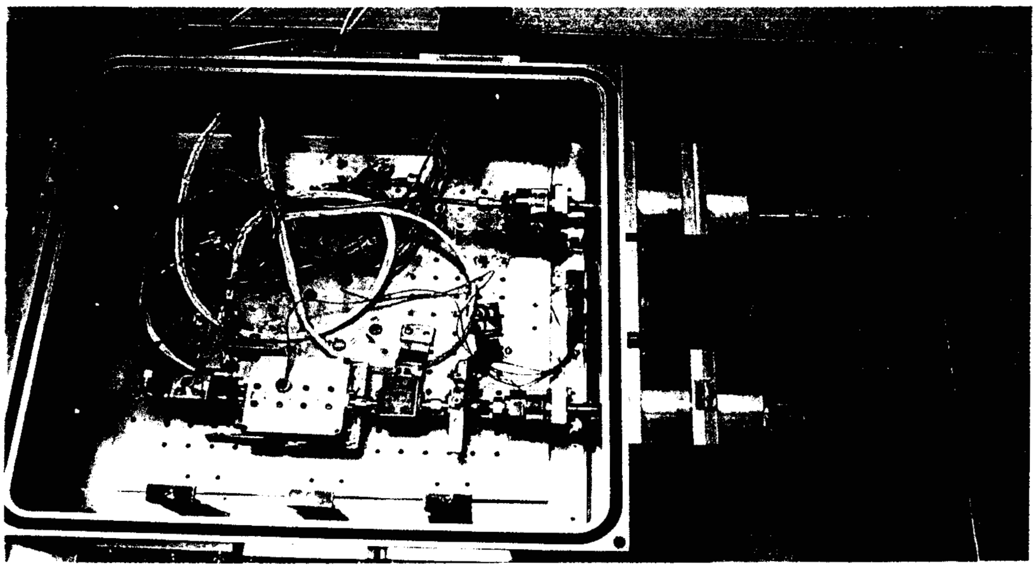

Figure 4. *X-band Amplifier Module in the Cryogenic Test-Bed. From lower right to left: HP346A Noise Diode, low loss 7mm input line, 7mm-3.5mm adapter, 20dB attenuator, isolator, amplifier module, isolator.*

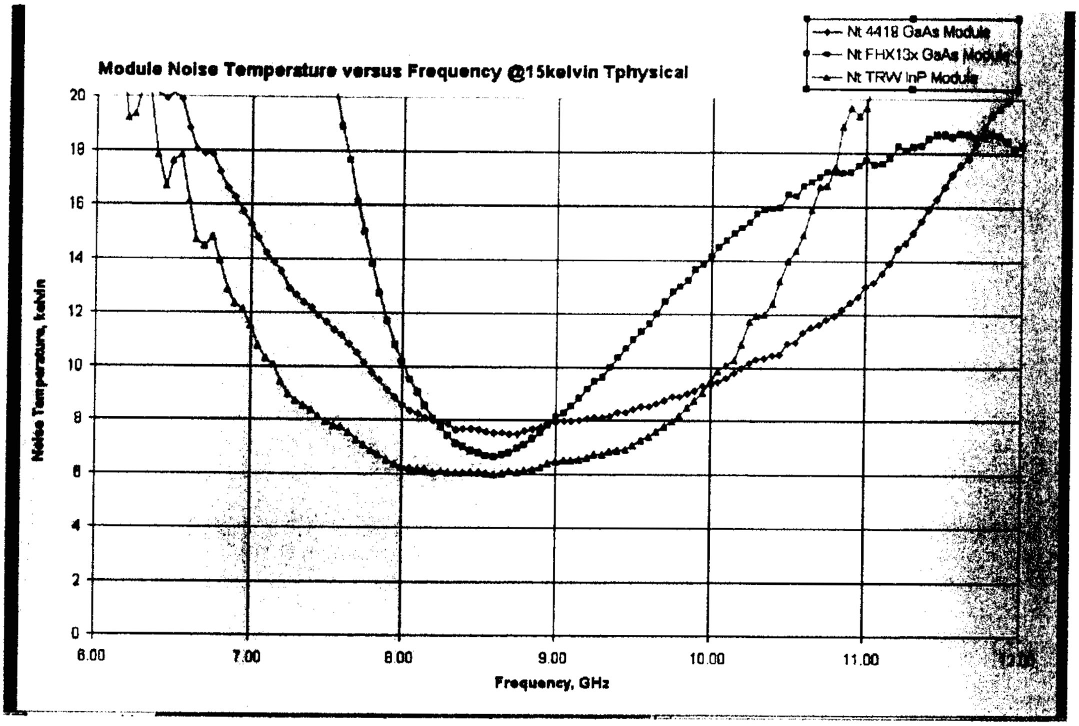

Figure 5. *Comparison of three different X-band 3 stage amplifier modules.*

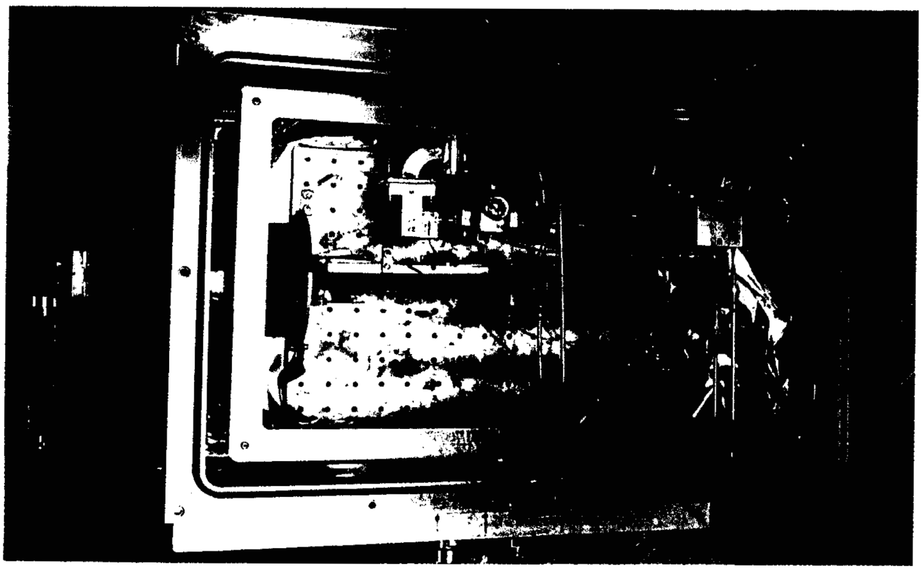

Figure 6. *X-band string test-bed with room temperature input on left. Waveguide attenuator is gray. Amplifier module is under US quarter dollar in the picture.*

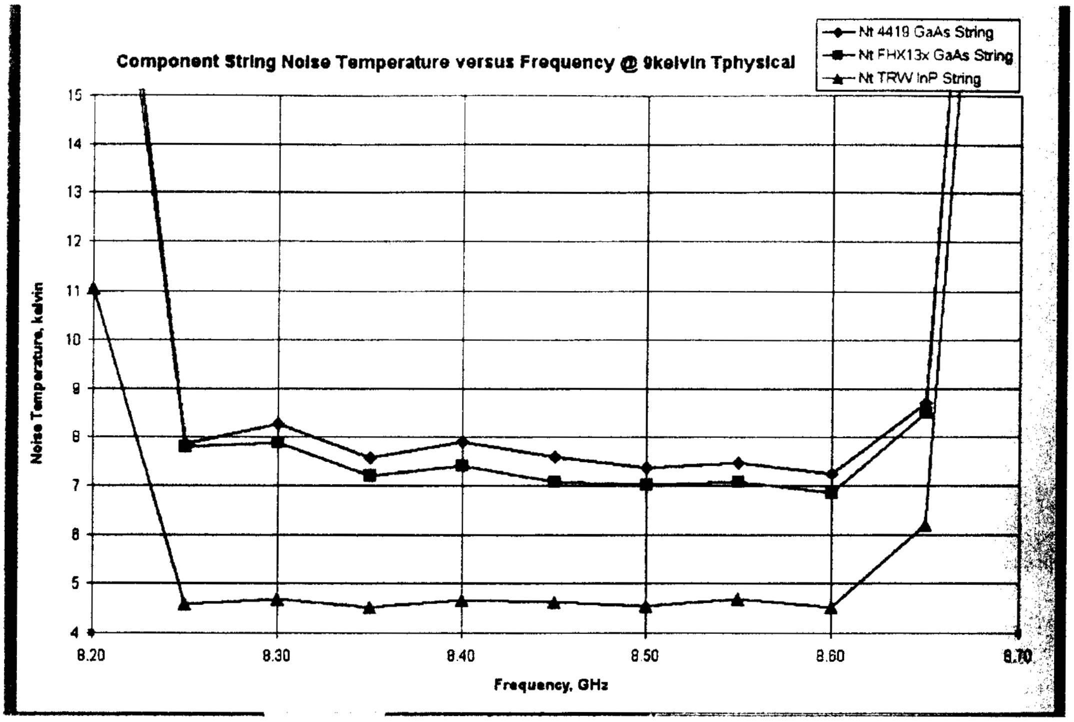

Figure 7 *Comparison of three different X-band component strings. Data referenced to cryogenic waveguide isolator input.*

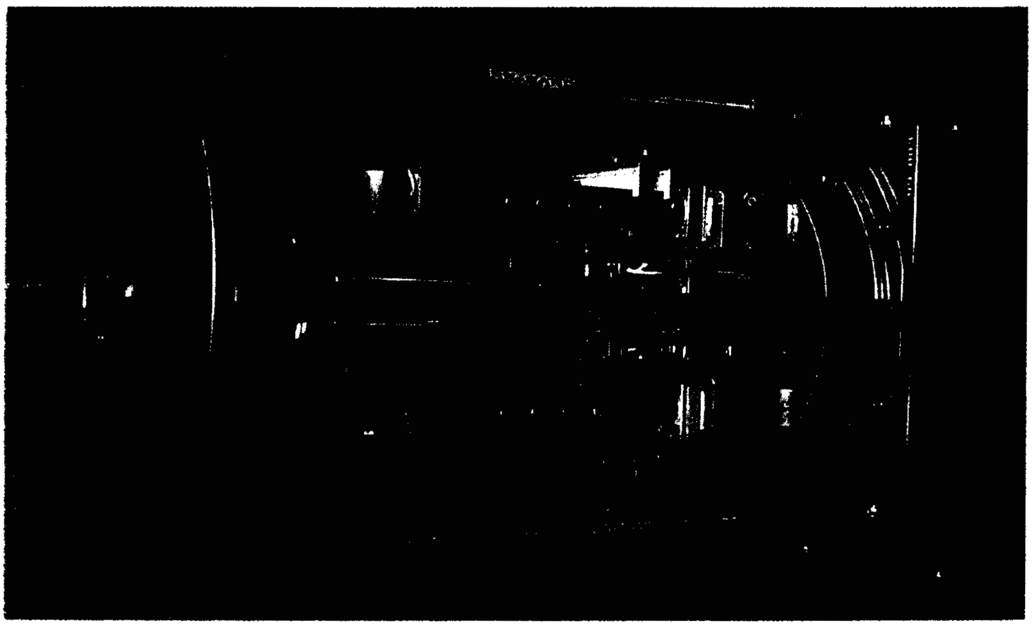

Figure 8. *X-band HEMT Closed Cycle Refrigerator.*

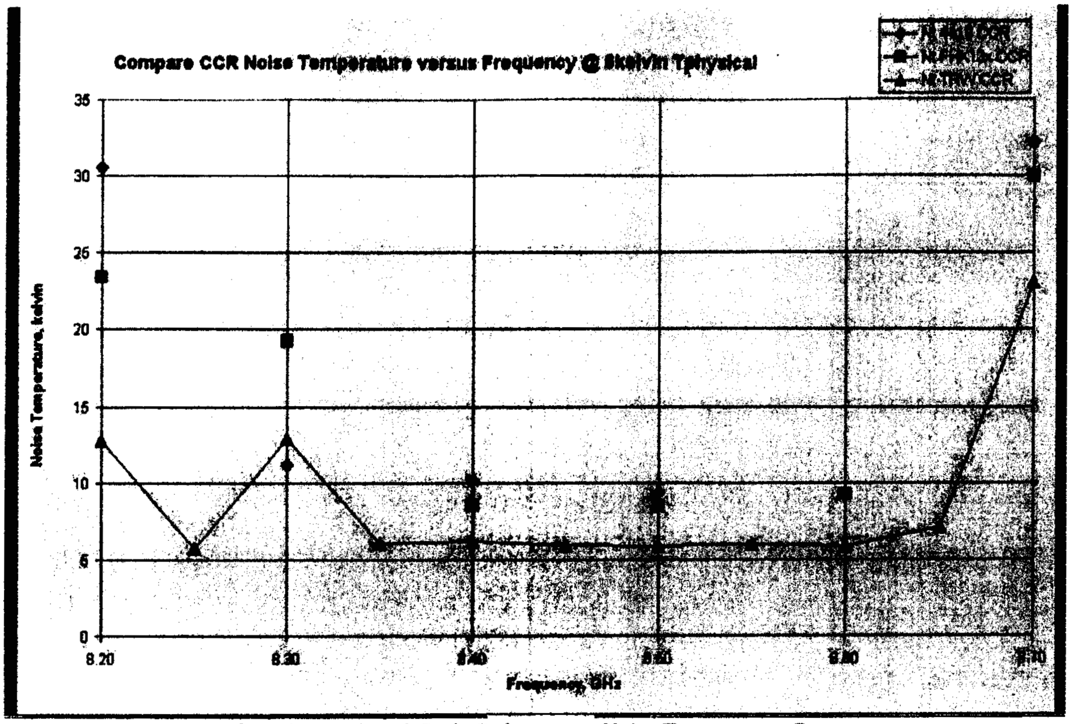

Figure 9. X-band Closed Cycle Refrigerator Noise Temperature Data.
This data is referenced to the room temperature waveguide input.

8. References

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